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Investigation of defects in epitaxial 3C-SiC, 4H-SiC and 6H-SiC films grown on SiC substrates

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ABSTRACT: Defects were investigated in SiC films grown on both Lely-grown and boule-grown SiC substrates. Etching with HCl was used to decorate defects in the vicinal (0001) SiC substrates and films. Line defects and micropipes in the boule-grown substrates were major sources of defects in the epitaxial films. Micropipes propagating into the epitaxial film were shown to be very harmful defects in pn junctions.

1. INTRODUCTION

Chemical vapor deposition (CVD) is commonly used to produce SiC device structures on SiC substrates (Davis et al 1991, Matus et al 1991). Previous work has shown that defects in the SiC substrates can affect the polytype and quality of epitaxial films (Powell et al 1991) and ultimately the performance of devices fabricated from these films. Defects, generated during the sublimation growth of boules, include voids, micropipes, and line defects (i.e. dislocations). The micropipes are tubular voids, of the order of a micrometer in diameter, that propagate along the c-axis growth direction. Additional defects are generated during the cutting and subsequent polishing of wafers obtained from these boules. SiC crystal platelets, grown by the Lely process, have also been used for many years as substrates. These can be used in the "as-grown" condition or polished "off-axis" to produce a growth surface that is at a small angle to the (0001) plane. Typically, the Lely crystals are free of micropipes and have a much lower density of dislocations than wafers obtained from boules. This paper describes an investigation of the impact of substrate defects on epitaxial films and subsequent device performance. In particular, micropipes were shown to cause premature reverse failures in SiC pn junction diodes.

2. EXPERIMENTAL

Substrates used in this investigation included 6H-SiC platelets, grown by the Lely method (Lely 1955), and boule-grown wafers of 4H-SiC (Moltech) and 6H-SiC (Cree). All samples were vicinal (0001) in orientation. In all experiments, the Si-face was used. The Lely samples were polished with tilt angles from near zero up to 1.5° from the (0001) plane. The boule wafers were either "on-axis" with tilt angle less than 1° or "off-axis" with tilt angles in the range 3° to 4°. Epitaxial 3C, 4H, and 6H films were grown at NASA Lewis by CVD

techniques described previously (Powell et al 1990, Powell et al 1991).

Prior to epitaxial growth on SiC substrates, an HCl etch at 1350 °C for approximately 20 min was frequently used to remove damage that is caused by cutting and/or polishing the substrate (Powell et al 1991). On the off-axis substrates, the HCl etch produced a smooth featureless surface, but on the on-axis substrates, the HCl etch decorated defects that are present in a manner similar to that caused by molten salt etches (Koga et al 1992). We believe that the difference in step density is the reason for this difference in behavior between on- and off-axis samples. At larger tilt angles (higher step density), the etching takes place at steps while at smaller tilt angles (lower step density), there is less competition from steps, hence, etching takes place at defects. The HCl etching procedure was used to decorate defects before and after epitaxial growth. Transmission electron microscopy (TEM) at Case Western Reserve University was also used to study defects in the SiC samples.

In order to study the effect of micropipes on device performance, n+p junctions were grown onto 6H boule wafers. The lighter p-doped side of the junction epilayers were at least 4 μm thick and doped to less than $2 \times 10^{16} \text{ cm}^{-3}$. Based on the high breakdown fields that have been experimentally observed on small-area 6H diodes (Matus et al 1991), the blocking voltage of these diodes would be expected to exceed 1000 volts. The resulting n+p junction samples were cut into 1x1 mm² pieces with a dicing saw so that micropipes could be observed in each piece with an optical microscope (transmission light mode). The micropipes were observed by sighting into these 1 mm² diodes in a direction parallel to the sample (0001) plane through the saw-cut edge. The 1 mm² diodes were I-V tested using a computer controlled measuring system with tungsten probe tips contacting a heavily doped cap layer and the substrate chuck contacting the backside of the the wafer.

3. RESULTS

A comparison of HCl etched surfaces of commercial on-axis SiC boule wafers and polished Lely platelets produced some striking differences. Hexagonal etch pits were generated in both types of substrates, as shown in Figure 1, but the pit density in the boule samples was on the

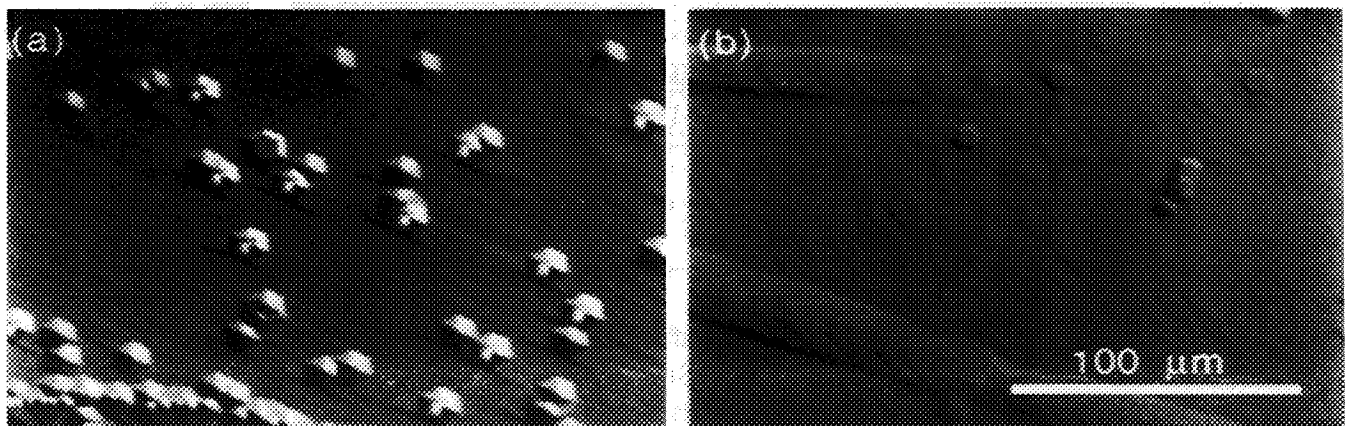


Fig. 1 HCl-generated etch pits in 6H-SiC in (a) boule wafer, and (b) Lely platelet

order of 10^4 cm^{-2} , an order of magnitude higher than the pit density in Lely samples. Pits also occurred along polishing scratches in both types of samples. Most etch pits in the boule samples were deep and inverted-pyramid-shaped, similar to those observed by Koga et al (Koga et al 1992) after etching with molten KOH. In contrast, almost all of the hexagonal etch pits on the Lely samples were shallow and flat bottomed. We believe that the flat bottomed pits are due to very shallow dislocation loops, possibly parallel to the surface, caused by cutting/polishing, and the inverted-pyramid-shaped pits are due to extended dislocations caused by the boule growth process. The pits generated in 3C epitaxial films grown on 6H boule samples were triangular and inverted-pyramid-shaped, suggesting that the dislocations propagate from the 6H substrate into the 3C film.

As reported previously by Powell et al (1991), 3C films grown on 6H substrates contain stacking faults, but we found that the 3C films grown on Lely substrates had approximately an order of magnitude fewer stacking faults than films grown on boule wafers (as few as 5 stacking faults in a $1 \times 1 \text{ mm}^2$ growth area. The lower defect density in the Lely substrates is believed to be a contributing factor.

We found that micropipes occurred in all 4H and 6H boule wafers we examined, and their density was on the order of hundreds per cm^2 . Sometimes a micropipe would have a gap in which the micropipe seemed to disappear and then reappear at some distance (e.g. about $100 \mu\text{m}$) further along its path. This indicates that either the micropipe decreased its diameter below that detectable optically or that the micropipe stopped and then started again. This latter case would suggest a dislocation is associated with the micropipe. Dislocation loops in the basal plane associated with micropipes have been observed (Yang 1993). In all cases in which we could observe a micropipe at an epi layer/substrate interface, the micropipe did propagate into the epi layer; however, sometimes the diameter decreased considerably in size within the epi layer.

The electrical and optical evaluation of the pn diodes yielded the following. A small number of the 1 mm^2 area n+p diodes exhibited rectification to reverse voltages beyond 1000 V. However, greater than 80% of the 1 mm^2 diodes failed at reverse voltages less than 500 V, well below predicted avalanche breakdown values. The typical reverse failure characteristics for a series of 1 mm^2 devices cut from the same n+p sample wafer are shown in Figure 2. At smaller reverse voltages, devices from the same wafer exhibited comparable leakages. When the reverse bias was further increased however, the devices each suffered a substantial sudden increase in current at largely differing voltages. The voltage at which the current suddenly increased is defined as $V_{J\text{Fail}}$, the junction failure voltage unique to each device. When the biased diodes are microscopically observed in the dark, clear evidence emerges that the junction failure takes place at specific points. The photograph of Figure 3 shows the highly localized microplasmas that typically become visible when the 1 mm^2 6H n+p diodes are reverse-biased beyond $V_{J\text{Fail}}$. Each point microplasma became visible at its own unique voltage, with no microplasmas being visible until the applied reverse bias exceeded $V_{J\text{Fail}}$ for each device. Though some diodes were observed to have failed along the saw-cut pn junction periphery, the vast majority of diode point failures occurred within the bulk junction area. By simultaneously observing a diode with an edge-on view while the diode was under reverse bias, the microplasmas and micropipes could be viewed simultaneously. The microplasmas were found to be located at the intersection of the micropipe and the np junction. This confirms that the

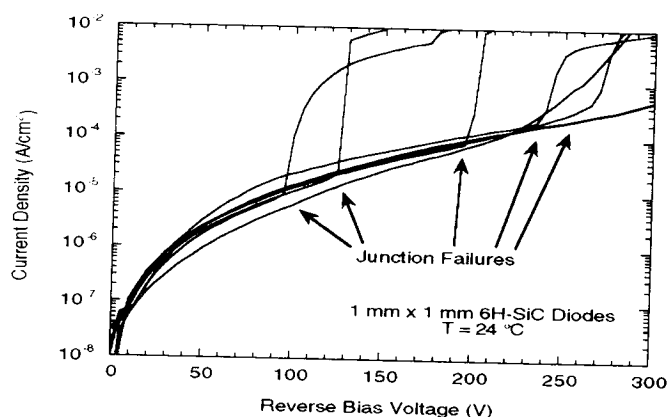


Fig. 2 Premature reverse failures in 6H-SiC pn junction diodes.

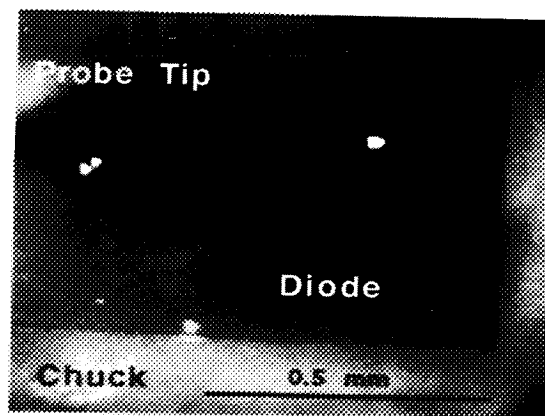


Fig. 3 Plan view showing microplasmas (four white spots) generated during reverse failure of pn junction diodes.

micropipes are associated with breakdowns.

4. DISCUSSION AND SUMMARY

We have shown that an HCl etch can be used to decorate dislocations in vicinal (0001) SiC with small tilt angles (less than 1°). The dislocations and micropipes in boule wafers propagate into the epitaxial layers with harmful consequences. Micropipe defects in 6H substrates were found to cause pre-avalanche reverse-bias point failures in most high-voltage epitaxially-grown 6H pn junction devices of 1 mm² or larger in area. This will severely limit the maximum operating currents of silicon carbide power devices. Until micropipes are significantly reduced from their present density (on the order of hundreds per cm²), 6H-SiC power device ratings will be restricted to around several amps or less. This defect must be dealt with through improvements in 6H-SiC crystal growth before the theoretically predicted advantage of SiC for power devices becomes a reality.

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